THE ALEXANDER GRAHAM BELL CENTENARY LECTURE

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"GRAHAM BELL—PIONEER: AN ERA OF OUTSTANDING DEVELOPMENTS IN WORLD COMMUNICATION"

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It is most appropriate that The Institution of Electrical Engineers should have decided to mark the centenary of the birth of Alexander Graham Bell, the pioneer in the development of the telephone—appropriate from the interest taken at the inception of telephony by The Society of Telegraph Engineers, the Society from which this Institution was formed, and from the contributions of so many of its Members to the complex and extensive branch of communications to which it has expanded. I appreciate greatly the honour of being entrusted with the delivery of this Centenary Lecture, but I find it most difficult to deal adequately with what should be attempted in such a lecture.

Sir Oliver Lodge, one of our most distinguished Honorary Members, gave a lecture before The Institution on the occasion of the Jubilee of the Telephone, 24th June, 1926, in which Bell's original telephone, his early work leading to his invention, and subsequent developments of telephony, up to the date of that lecture, were described in the classical and incomparable way in which that great master could illuminate a subject. Having in mind that lecture, and also the many other records of Bell's life and work and subsequent developments, I have confined myself to a brief recapitulation of the more outstanding historical facts, and a résumé of some of those phases of subsequent telephone developments which most closely derive from Bell's experiments.

Alexander Graham Bell was born at 16, South Charlotte Street, Edinburgh, on the 3rd March, 1847. He was educated at McLauren's Academy and at the High School in Edinburgh, and for one year he attended Edinburgh University. Subsequently, he attended University College, London. His education included training in music and the study of telegraphy. His family moved to Brantford, Ontario, in August, 1870, and later to the United States, of which he became a citizen on the 16th November, 1882. He died at Baddeck, Nova Scotia, on the 2nd August, 1922.

Bell's earlier work was concerned with the training of the deaf and dumb, which led him to the consideration of means for the accurate production of human speech by instrumental means. The idea of getting the deaf to interpret musical sounds transmitted by what he called the "harmonic telegraph," making a kind of modified morse-code system, led to his experiments on telegraphic communication using tuning forks.

In 1872–73 he developed this system of harmonic telegraphy using electrically-driven tuning forks. Briefly the scheme was that two similar sets of forks of different pitch were employed. The driving coils of each of the transmitting forks were connected through keys to an earthed battery, the other end of the coil passing through contact breakers on the tuning forks to a common line-wire. At the one end, all the driving coils were connected to the line wire in series, and at the other end direct to earth. On throwing any one key, the transmitting fork was set into vibration and transmitted an interrupted current over the line. At the receiving end, only the fork having the same pitch as the driving fork was fully vibrated. Later, in 1873, he substituted vibrating reeds for the tuning forks.

[At this point was demonstrated a piece of apparatus showing the principle on which the harmonic telegraph operated.]

During these experiments the idea occurred to him that speech was the resultant of several simultaneous vibrations, and that, if a thin delicate membrane could move the relatively massive bones of the ear, similarly a larger and stouter membrane should be able to move a piece of steel.

In February, 1875, Bell went to Washington to file his telegraph patent (U.S. Patent 161739, filed 25th February, 1875, dated 6th April, 1875), and while there he called upon Professor Joseph Henry, Secretary of the Smithsonian Institute, and told him of his various discoveries, asking his opinion whether any of these were new or old. He took the opportunity to advise Professor Henry of his idea that an adaptation of his harmonic telegraph using a membrane carrying an iron plate before a magnet might enable the human voice to be transmitted by telegraph. Henry said he thought that Bell had the germ of a great invention, and advised him to continue to work on it.

While Bell was experimenting with the tuned-reed telegraph the make-and-break contacts of one of the transmitter reeds came into permanent contact, and on plucking the reed he heard a musical note, thus proving definitely that a magneto-electric current generated by the vibration of an armature in front of an electromagnet would produce audible effects that could be used for the purpose of multiple-telegraph and possibly of speech transmission. Success may be said to have been recorded in July, 1875, when he tried a membrane to which was attached an iron armature free to vibrate near a magnet, and he patented this shortly afterwards.

In 1876, at Boston, Bell demonstrated his telephone to Sir William Thomson (Lord Kelvin) to whom he gave the instrument as a memento. Its possibilities were immediately apparent to Thomson, and the interest he displayed and the encouragement he gave did much to give an impetus to its adoption as a practical instrument.

It is interesting to recall that the first personal contact Bell had with this Institution was in the following year, 31st October, 1877, when he described his researches to The Society of Telegraph Engineers.

One hundred years ago communication by means of the electric telegraph was being practised. For the most part, telegraph signals were then read from the direction of movement of a galvonometer needle. Visual reading of the signals was, however, being replaced by audible reading, as it was found that operators could read from the sound made by the movement of the armature of an electromagnet. The Wheatstone A.B.C. transmitter and receiver were in use, and the morse code was coming into favour.

At the time of Bell's invention in 1876, in addition to manual sending by morse code, Wheatstone's high-speed system, using

* Cable and Wireless Ltd.

perforated tape for sending and markings on tape for receiving, which had been developed in 1858, was in use. Attention was being given to devising means for the direct printing of roman characters on tape, and both Baudot and Hughes had invented systems for doing so which withstood the test of time. At about this time also, much attention was being given to the development of telegraph relays, though the idea is much older; the first mention on record is of a device called an electrical renewer, by Edward Davy (about 1837). The first submarine telegraph cable from this country was laid across the English Channel in 1851; it had gutta-percha covering only, and it quickly failed. A cable with an iron sheath added was laid soon afterwards, and a direct London–Paris telegraph circuit was established in 1852. The story of the first transatlantic cable is well known; after great endeavour, telegraphic communication between this country and America had been established about ten years before telephony was proved to be possible.

Multiplex telegraphy also dates back to Edward Davy, who conceived the idea (1838) of sending two or more signals simultaneously. Following many workers in this field, Baudot invented a multiplex telegraph which, after development, was introduced on British overseas communications in 1897 and later became a standard system on our inland telegraph network. This system of multiplexing divides the time required for transmission over each of a number of separate telegraph channels (generally 4) between them and so enables them to be worked concurrently over the same line. Baudot's great invention for telegraphy just preceded Bell's historic discovery for telephony.

This then was the position of the art in telegraphy when Bell's own experiments on the harmonic telegraph led to his discovery that a single vibrating element at each end of the line would transmit the complex waveforms of speech sounds with sufficient accuracy for them to be easily identified by the ear.

The device which Bell invented as the result of this discovery is now called a telephone receiver; it is reversible in operation and can also be used as a telephone transmitter, so that two similar instruments, both for speaking and listening, can be used as a "telephone"—as was originally done. The carbon-granule microphone, which superseded Bell's instrument as a transmitter, is irreversible in operation and cannot be itself be used as a "telephone," but it made telephony beyond very short distances practicable.

Of all the many and great changes which the development of the technique and apparatus of telephony have brought about since the early days of the use, in combination, of Bell's receiver and the carbon-granule microphone, the changes in these two instruments are perhaps the least significant. Improvements there have been, of course, particularly in the quality of the materials used and in the manner of their assembly, but, for the most part, these improvements are slight in relation to the great amount of experiment and effort which has been expended to produce them. Only recently, as a result of the application to acoustical and mechanical design of techniques based on analogies to electric circuit theory, have substantial improvements in the quality of the performance of these instruments been brought to a practical form. In particular, the effects of mechanical resonance can now be eliminated and the sensitivity of the instruments maintained at the higher frequencies transmitted in commercial telephony. That telephone instruments improved on these lines have not yet been brought into general use in this country is due partly to the war and partly to the magnitude of the task of replacing subscribers' telephones, which exist in millions distributed throughout the whole area of telephone service.

[Comparisons between the Bell telephone and the carbon-granule microphone as transmitters, and between the carbon-granule microphone and the modern receiver, also as transmitters, were demonstrated.]

Initially the pressure for developing telephone service was exerted towards extending the distance over which it could be given and in dealing with the complications involved in arranging for the setting up and clearing of calls between members of an ever-expanding subscriber population.

The first step towards extending the distance of telephone usage was the introduction of the carbon-granule microphone, which increased the possible range from tens to hundreds of miles. One of the longest unrepeatered telephone routes used in this country was that from London to Glasgow, a distance of about 400 miles. It was carried on open-wire conductors weighing 800 lb per mile, the overall attenuation of which was theoretically 8 db, but in practice about 16 db.

The search for a telephone repeater to perform a function similar to that of the telegraph relay was intensive. Telegraphy was effected either by make and break or by reversal of current according to the morse code, the signals transmitted being detected by sensitive instruments at the receiving end. Great distances could be worked, either by slowing down the rate of signalling to a speed at which the system could operate—as was necessary for long submarine cables—or by inserting in the transmission line relays or repeaters which could receive the signals and retransmit them with augmented power derived from an electric battery. Slowing down the speed is clearly not applicable to telephony, but a repeater is.

The most promising line of development for a telephone repeater—prior to the advent of the thermionic valve—was the simple expedient of mechanically coupling devices similar respectively to the Bell receiver and the carbon-granule microphone, thus making use of the feed current to the carbon-granule device as a source of power for amplifying the retransmitted sounds. Unfortunately, the distortions inherent in the carbon-granule microphone, when dealing with the wide range of frequencies and amplitude existing in speech, are such that, though they can be tolerated if they occur only once, they render the speech sounds unintelligible if they are allowed to operate a few times on a transmission of speech. Consequently, useful application of the telephone repeater had to await the arrival of the thermionic-valve amplifier.

The thermionic amplifier, used as a telephone repeater, has provided the solution to the problem of achieving distance over land communications. The distance problem cannot, however, yet be regarded as completely solved for telephony. The telegraph cable laid across the Atlantic in 1866 gave successful telegraph communication between this country and America. There is, as yet, no corresponding means of telephone communication by cable. It is true that telephone communication across the Atlantic has existed for the past 20 years by wireless, and this fact, by taking the edge off necessity, has probably somewhat deferred the introduction of a transatlantic telephone cable, but the number of simultaneous conversations which can be carried by radio links is limited to the number of frequency allocations available.

For a few years after the introduction of the telephone, telegraph practice was followed, in the use of galvanized-iron wire for the overhead lines. The search for more suitable material for the conductors, from both the electrical and the mechanical aspects, introduced copper and bronze wires of kinds such as are now in use. Congestion of the overhead lines, caused by expansion of the service, led to the need for replacing them by underground cables, first for local distribution in towns and later for main trunk routes.

The earliest underground cables, also, were similar to those

then in use for underground telegraph lines, i.e. copper conductors covered with gutta-percha. Such cables, being inefficient for telephony transmission, were superseded by dry-core paper-insulated lead-covered cables, in which the individual copper conductors are separately covered by a loose wrapping of paper, the whole being enclosed in a lead sheath. The paper acts as a separator, and the dielectric is principally air, so that the capacitance between conductors is much reduced. Very extensive development has gone into the design and manufacture of these cables, particularly in finding measures to reduce capacitance and to minimize crosstalk by balancing the mutual capacitances between the wires in different pairs.

The significance of the effects of the electrical constants of a line on its ability to transmit alternating currents was first expounded and published by Oliver Heaviside in 1887. A practical application of his theory took the form of adding inductance at intervals along the line to compensate (over a limited range of frequencies) for the predominant effect of capacitance—a practice known as "loading the line." In this country a trunk circuit between Liverpool and Warrington is recorded as having been loaded as early as 1903. The advantages of loading in reducing the amount of copper per circuit and extending the useful distance range of underground cable were more fully realized at a later date. An important example was a loaded main cable connecting London, Birmingham and Liverpool, completed in 1916, which was designed to accommodate 72 circuits. It is of interest to note that the advantages of loading can apply only over a restricted range of frequencies, and loading was at that time adjusted for carrying one telephone circuit only per cable pair. At high frequencies a loaded line exhibits a cut-off effect similar to that of an electric filter—a form of which, in fact, it is. With the modern practice of carrier working, using the same conductor for several simultaneous telephone conversations by extending the range of frequencies transmitted, this kind of loading is disadvantageous.

[The effects of filtering out certain of the bands of frequencies of which speech is composed were demonstrated.]

The invention and development of the thermionic valve opened up an era of progress in communication by wireless which was greater in magnitude and speed than the effect it had on communication by wire. Wireless telegraphy had been practised for several years, the radio frequencies being generated by electric spark, by the Poulsen arc or by high-frequency alternators, but it needed the thermionic valve to make wireless telephony on any large scale commercially practicable. Aided by the fact that signals could be received by very simple apparatus, the broadcasting of wireless telephony became popular in this country from its inception in 1922. Thus a new and progressive industry was launched, much to the benefit of all forms of telecommunication. Another form of telephone receiver, namely the loudspeaker, came into widespread use, and much development work has been done on it. Originally it used the principle of Bell's telephone, but now the usual method of electromechanical conversion is the generation of force on a conductor (a moving coil) instead of on ferromagnetic material.

On the 1st January, 1926, world-wide wireless telegraph communication from a single radio-transmitter at Rugby was brought into service. The service was essentially of a broadcast nature intended especially for ships, the transmissions being sent in all directions. In January of the following year a wireless-telephone service was opened between this country and the United States, using, in this country, a low-frequency radio transmitter, also at the Post Office radio station at Rugby, a radio receiver at Cupar in Scotland, and terminal equipment in London for uniting the two separate, outgoing and incoming, transmission paths over the radio link to a two-wire circuit for connection to subscribers on the British telephone network. This was not a broadcast service but a link between users of telephones in America with those in Europe who had access by telephone to London over land line and the short submarine cables between this country and the Continent. The transmitter for the low-frequency transatlantic radio service has since been modified to carry two simultaneous telephone channels, one centred at 60 kc/s and the other at 68 kc/s.

Apart from its historic significance there are some interesting and (at the time) unique features about the method of transmission used for this radio link. It uses the single-sideband suppressed-carrier technique, which differs from that of ordinary broadcast telephony in that power is saved by transmitting the carrier at low level (special means have to be provided at the radio receiver for reinserting or boosting the carrier to a high level), and both power and frequency bandwidth are economized by transmitting only one sideband, namely those frequencies immediately above or below that of the carrier. This technique is now in very general and widespread use in multichannel, or carrier, systems of telephony over cables. Its advantages would apply to broadcast telephony, but for that service they are offset by the added complexity which would necessarily have to be embodied in each receiving set.

With progress in the design and manufacture of thermionic valves the generation of stable alternating current, suitable for radiocommunication, at higher and still higher frequencies has been possible. Extension beyond the medium frequencies, used for broadcasting, to the high frequencies (3 000–30 000 kc/s) enabled use to be made commercially of Nature's remarkable gift of ionized layers in the upper atmosphere which reflect wireless waves of frequencies in this band. Thus sky waves reflected, perhaps several times, from one or other of these layers can travel round the earth from transmitters whose power, as judged on standards for ground-wave propagation from a low- or medium-frequency transmitter, is ridiculously small. Moreover the wavelengths concerned are sufficiently small to allow quite highly directional aerial structures to be erected, thus further economizing power by concentrating the radiated beam and the receiving aerial on the desired direction.

Several inter-continental telephone services have been opened up by high-frequency radio links; as an example of extreme distance, a service between this country and Australia was started in April, 1930. Nature's gift, however, has its price; propagation by reflection from ionized layers is not wholly reliable, and much effort has been put into ways and means of making the best of it. Studies and records of propagation have been made with a view to forecasting the best frequencies for use at different times of day, seasons and sunspot cycles for each radio path; diversity reception, taking advantage of local variations in receiving conditions, and the musa (multiple-unit steerable antenna) system, devised to select the strongest down-coming ray and to eliminate much of the interference by other rays, are means to this end. The very fact of the ease of propagation of high frequencies makes them particularly liable to produce or suffer interference, so that the problem of sharing frequencies is world-wide and the number of frequency allocations available is less than is required to meet all demands.

At still higher frequencies useful radio propagation tends to become limited to the optical range. Use has been made of the very high frequencies to extend the telephone system across short sea-crossings by radio link instead of, or supplementary to, submarine cable. A single telephone circuit was provided in this way across the Bristol Channel in 1932, and six separate circuits were provided between Scotland and Ireland in 1934; since then a number of radio links have been established in the inland network, mostly with the Scottish islands. The tendency

of modern practice is to treat such a link, in effect, as a repeater section in a multi-channel telephone route, rather than to provide a separate radio circuit, with audio-frequency terminations at each end, for each telephone circuit over the link.

During the last war intensive development, particularly for radiolocation, brought very much higher frequencies into use, namely frequencies of ten million kc/s and more. These frequencies have been used also for multi-channel telephone communication by a technique which is different from the now conventional method of division of the frequency spectrum for separating channels. By radiating extremely short pulses and synchronizing the reception, the telephone channels can be separated on a time-sharing basis, similar in principle to that of Baudot's multiplex telegraph.

No radical change in propagation phenomena, such as was found with high frequencies, has been observed at these very high frequencies. Abnormalities of propagation which can sometimes occur are attributable to atmospheric conditions associated with the weather. The range of reliable use is restricted to optical paths, and as the frequency is raised so does the means for radiating a sharp beam become more compact.

It is technically practicable to transmit and receive bandwidths some megacycles per second wide at very high frequencies by radio links over optical paths. It is therefore possible that such a means of transmission may be put to use on overland routes for carrying large numbers of telephone circuits or for relaying television signals.

I return now to take up the thread of the progress of transmission over lines. Following some trials of thermionic-valve amplifiers used as telephone repeaters, the first repeater station in this country was opened in 1916 in Birmingham, on the London–Liverpool cable route. The planning of the telephone network was thereafter based on the use of repeaters. Installed at intervals of 40 or 50 miles, each repeater restores the power of the speech currents to its original level, so that no limit is set to the distance of wire telephony over land where repeater stations can be maintained. Although amplification can be given almost without limit there is a limitation to its effectiveness.

[The effect of amplifying weaker and weaker signals in the presence of noise at constant level was demonstrated.]

The next phase of major development was to concentrate on the problems of coping economically with the growth of numbers of telephones and lines requirements, and of effecting improvements in the quality of the service. In long-line transmission the outstanding result has been multi-channel, or carrier, telephony, in the success of which designers of cables and of amplifiers have both played major parts. Carrier telephony, as it exists in this country to-day, has terminal equipment at each end of the line, where a number of telephone channels are combined, each being allocated a band of frequencies 4 kc/s wide to form a wide-band transmission; thus 12 channels can be accommodated in the band 12–60 kc/s. The whole band is transmitted and amplified at each repeater station on the route, and the amplifiers are equalized to fine limits to compensate for variations with frequency of the transmission on the cable. It is, perhaps, of interest to note that the principle employed is that of providing frequency discrimination in the terminal equipments for separating transmissions over a common line. This principle, though very different in its manner of application, is the same as that of the harmonic telegraph on which Bell first heard telephonic sounds.

At first the development of carrier working was limited to the addition of a few carrier channels to the normal, or audio, telephone channels. Limitation was set by the bandwidth of the frequencies which could be effectively transmitted over the cables. A 12-channel carrier system (12–60 kc/s) over unloaded cable was introduced into this country, first on a route between Bristol and Plymouth in 1936, and this system has been extensively installed. A separate cable is used for each direction of transmission, so that two 24-pair cables provide 288 trunk circuits. The maximum spacing of repeater stations was (in this country) 22 miles for the early installations; it has since been lowered to 15 miles to enable the frequency bandwidth to be widened to 12–108 kc/s and thus provide for 24-channel working.

The ten years just passed have seen a vast stride forward in the development of carrier telephony by the use of coaxial cable. The cable is very simple in form; it consists of two conductors only, an outer tube containing an inner tube, or wire, running along its axis. Suitable means for maintaining accurate separation between the two with insulating material of good dielectric properties is not so simple. Such a cable enables what only recently was regarded as a phenomenally wide frequency band to be transmitted effectively and ecomically. The first coaxial cable route in this country, between London and Birmingham, was put to commercial use in 1938 and has been carrying traffic ever since. It has an outer tube diameter of 0·45 in, and, with repeaters about 8 miles apart, an effective bandwidth of 0·5–2·1 Mc/s. It now carries 280 telephone circuits, which is considerably less than its ultimate capacity. Separate tubes in the same cable carry the channels for the two directions of transmission. The coaxial cable technique is developing rapidly, both in improvements and in extent of application. The latest system now being installed in this country has a bandwidth of 60–2 850 kc/s, with repeater stations about 6 miles apart, providing a total traffic capacity of over 600 telephone circuits.

The ability to transmit wide frequency-bands has application not only to telephony, but also to television, for routing programme signals to the radio transmitters. The problem is more difficult in television, because equalization of phase as well as amplitude is necessary for television but not for telephony.

Mention is due to a few of the inventions which have made this spectacular expansion of wide-band telephony practicable. Black's application of negative feedback to amplifiers made practicable the design of very stable amplifiers for the coaxial cable repeaters, capable of handling the wide frequency-band with so little distortion of the signals that interference due to interaction between different frequency components is sufficiently low. The design of electric filter networks is not so new, but these are essential components in the terminal equipments, where the telephone channels are combined or separated. The introduction of quartz-crystal elements as reactors in filter networks has permitted much sharper filtration than was possible with normal inductors and capacitors. The development of the quartz-crystal element as a means for generating alternating currents of extremely stable frequency has also been invaluable to telecommunications generally and particularly to radio. The use of metal rectifiers has greatly facilitated the design, in compact form, of the modulators and demodulators needed in conjunction with the filter networks, for translating the telephone frequency bands to any desired part of the spectrum.

In telegraphy multi-channelling is not so novel as in telephony; it was done on a time-division basis, for example in Baudot's system, to which I have referred earlier. With the rapid growth of the telephone network, the alternative method of frequency division became attractive. Telegraph signals, sent at normal speeds, need much less bandwidth than that used for a telephone channel; thus each telephone circuit is, for telegraphy, a wide-band circuit. By translating telegraph channels into the frequency range of telephony, a number of separate telegraph messages can be sent along one telephone channel—thus per-

mitting the integration of the hitherto separate telegraph and telephone networks.

In the early 1930's this technique (known as multi-channel voice-frequency telegraphy) was extensively applied in Great Britain as part of a planned reorganization of our telegraph system. At the same time teleprinters, in conjunction with phonogram working (the sending of telegraph messages by telephone) replaced all earlier systems of telegraphy in the inland system. The voice-frequency telegraph system commonly used in this country has 18 channels, each 120 c/s wide. The transmission of pictures over telephone channels (line or radio) represents a merger of the telegraph and telephone arts which has been practised for the past twenty years.

I turn now to Oversea Transmission. Submarine cables have a unique place in world telecommunications. The transatlantic telegraph cable laid in 1866 remained in service only ten years, and not without many interruptions. In 1900 the number of cables crossing the North Atlantic was 13, and in 1921 it was 21; these figures illustrate an expansion which, of course, was not confined to the North Atlantic but applied to all the main ocean telegraph routes. Experience in the protection of these cables from their many enemies resulted in a multi-layer construction, namely gutta-percha for insulation, brass tape for protection against marine borers, jute to act as a cushion for the armour sheathing. On some cables the central copper conductor has first a wrapping of ferromagnetic material to give continuous loading and so improve transmission. Thus the 1926 Fanning Island–Bamfield cable (3 458 nautical miles), loaded by Mumetal wire 0·02 in in diameter is capable of carrying 250 words per minute (simplex working); the older unloaded cable on this route worked 25 words per minute (duplex).

International telephony was inaugurated in this country in 1891 by the bringing into service of the first submarine telephone cable across the English Channel. The cable had four cores and enabled two telephone circuits to be set up between London and Paris. Loading was introduced on a cable laid across the English Channel in 1910, the loading coils being incorporated in the cable, joined in at spacings of one nautical mile. The early submarine cables mostly used gutta-percha for insulation—a material which is not suitable in the transmission of the higher frequencies required in telephony. The first paper-insulated continuously-loaded 8-pair cable from this country was laid to Holland in 1924. Modern submarine telephone cables use polythene, a plastic which has remarkable dielectric properties at high frequencies. Coaxial cables laid across the English Channel in the later stages of the war are carrying 60 telephone circuits each.

Distance remains a limitation to telephony by submarine cable. If repeaters can be added into the cable at intervals along its length, distance can be increased, or, alternatively, the number of circuits worked over a given distance can be increased. A submerged repeater differs from a land repeater in that it must receive its power supplies over the cable, and it must be so stable and reliable that it can operate without any maintenance for very long periods. The first submerged repeater was laid in June, 1943, on the Holyhead–Isle of Man cable; another was laid last year on the Anglo-German cable. These repeaters have more than doubled the number of telephone circuits which are carried. A telephone cable with submerged repeaters presents much more difficulty and financial hazard on long deep-sea routes, but it is known that the Bell Telephone Laboratories have been studying the problem for several years.

In this connection attention may be drawn to the figures of the availability of telephone circuits between London and certain other parts of the world, prior to the recent war.

London and	*Number of telephone circuits*
Paris	93
Moscow	1
New York	5 (by radio link)
Australia	1 (by radio link)
China	0

The figures can scarcely be taken to represent the potential demands for telephone communication with these centres.

The frequency bandwidth which would be usable for telephony on any long-distance submarine cable would be very valuable and could justify exceptional measures being taken for its most economical use. Some studies are now being made of the transmission of speech from an approach different from the simple one of direct transmission of the waveforms of the currents sent out by the microphone. The waveforms for speech vary in an irregular manner, but not generally at a very rapid rate, from one State to another. If advantage can be taken of the comparative slowness of the rates of change, bandwidth economy can perhaps be effected by limiting the information transmitted to what is essential concerning these changes.

A piece of practical apparatus, based on the analysis and synthesis of speech sounds, is available which illustrates the new outlook. It is called a Vocoder, a contraction of the words "voice" and "coder"—a name given to it by its originators in the American Telephone and Telegraph Co. It consists of an analyser at the microphone end of the line and a synthesizer at the receiver end. The analyser breaks down the waveforms of the speech currents into eleven "packets" of information; these packets are separately transmitted, as a running commentary, to the synthesizer, which uses them to build-up local sources of voice-frequency currents into waveforms similar to those received by the analyser. Of the eleven packets, ten can be taken (for purposes of simple explanation) as representing information about the state of the acoustic resonators formed by the mouth, while the eleventh conveys information about what the larynx is doing. Although there are eleven transmission channels, the speed of signalling on each one is low, and it is estimated that they could all be accommodated in a bandwidth of about 300 c/s, as compared with about 3 000 c/s for normal telephony.

[The Vocoder was demonstrated, first with the larynx control, or pitch channel, disconnected, then with this control set to reproduce speech in monotone, and finally to reproduce normal speech.]

Some reference, though necessarily brief, is due to the part that has been played by researches into the production of new materials. The design of telecommunication equipment and the development of new techniques have repeatedly benefited as a result of materials having useful properties becoming unexpectedly available. For example, the original synthesis by Dr. Baekeland of phenol-formaldehyde resins and the polymerization of ethylene by Imperial Chemical Industries were both carried out without any particular regard to the requirements of telecommunications. Materials resulting from the first named, revolutionized the design of telephone instruments, and from the second facilitated the development of cables and other apparatus for use in high-frequency circuits. I have mentioned earlier the use of polythene in submarine cables. Future developments in telecommunications which may result from entirely new combinations of properties of materials cannot be foreseen, but the industry is becoming equipped to take the best advantage of modern knowledge of material structure to enable materials giving special characteristics to be designed for its use—rather than having to rely solely on selection of the best of materials which happen to be available. Important properties of materials

generally useful in telecommunications are electric, dielectric, magnetic, mechanical, piezo-electric; these, too, have subdivisions, and development for a particular application may need emphasis on any combination of properties.

I can afford only a brief mention of another and technically very different aspect of telephony which has received at least as much development effort and ingenuity as transmission, to which my remarks have mainly been confined. I refer to the techniques of switching and signalling whereby the means are established for setting up and clearing down all the calls made by telephone subscribers. Any large automatic exchange will indicate the size and complexity of the systems now in use. In a sense the applications of these techniques are local rather than world-wide, since each switching centre, or exchange, serves a local population. Exchanges in a large city are interconnected for automatic dialling by subscribers, within the range of signalling by d.c. impulses. Connections between more remote centres of population are established by telephone operators. A system has, however, been developed, and is in use on a number of long-distance circuits in this country, whereby signals of voice-frequency currents, instead of direct current, are used to effect the necessary switching operations. Either signals or speech may be present on the line, so that the receiving equipment has to be capable of distinguishing between the two and operating only on the former. The system enables the controlling operator at the calling subscriber's end of the circuit to complete a connection to a subscriber in a distant town without the assistance of a second operator. Subscriber dialling on a national—even an international—basis is also technically possible by such means, if certain practical difficulties can be obviated. Switching and signalling have always received great attention in their development, and further progress on novel lines may confidently be expected.

In this review I have, by way of illustration, made reference to various developments as applied in Great Britain. It is, of course, not to be inferred that all the developments originated in this country. For many of them, in fact, we are indebted to that great country wherein Bell made his classic discovery, little more than seventy years ago.

In retrospect, the devices of the early years of telephony seem very elementary. That such an edifice as modern telephony has been built up on such a comparatively crude fundamental basis is a tribute to the ingenuity of many engineers, in many countries, who followed Bell, and I feel it is to the very practical insight and acumen of Bell, rather than to his scientific research, that we should pay tribute.

Perhaps the greatest tribute of all should be paid to the greatest of all engineers—Nature herself—who in the design of the ear and its nerve system gives us an amazing device—sensitive to a range of frequency from less than 50 to more than 15 000 c/s; discriminating between sound pressures ranging from less than one thousandth to more than one thousand dynes per square centimetre; tolerant of interference and departures from correct frequencies and levels to a remarkable extent; interpreting and giving intelligibility under conditions which would be intolerable to any mechanical device.

I have indicated how Bell's success in producing his telephone followed his work on his harmonic telegraph. Thereafter telephony developed on independent lines: separate line networks were used; methods of transmission and amplification were essentially different. Latterly the developments in transmission have merged together, telephone lines being used for telegraphs as in voice-frequency telegraphy. Telephone technique has aided the development of telegraphy. Now, with such devices as the Vocoder, in many respects akin to telegraphy in its transmission, the possibilities are opening out for telephony to make use of a form of telegraphic transmission on long-distance submarine cables.

In paying tribute to the work of Alexander Graham Bell on this centenary of his birth, it is fitting that we should include in this review the great advances of this earlier means of communication by electric signals. So much of these advances is the sustained development of his great discovery that the vibration of an armature in the field of an electromagnet could be used in a reversible manner for speech transmission.

In preparing this lecture I have had much information placed at my disposal from many sources, particularly on Bell's early life and work, more in fact than I could include in the time and space available. I am much indebted to these contributors, and I would particularly place on record my appreciation of the contribution of Mr. West and his colleagues at the Post Office Research Station for much of the information in the text and the demonstrations they have given this evening.